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A qualitative model of the reliability-maintenance cost relation of critical hydraulic structures in support of complex modeling and communication of model results

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The flood protection of the Netherlands critically hinges on the full readiness of their storm surge barriers. A strict form of risk-based asset management is applied to ensure a good condition. This method relies on detailed reliability models that explicitly link maintenance to performance. In this way, safety standards should be met in an efficient way and without unnecessary maintenance investments. Nevertheless, the necessity of investments often appears hard to explain. This may be caused by the fact that the reliability models rely on strong but implicit assumptions about how the maintenance is performed. Therefore, one could question the credibility and usability of the aforementioned models.

Here, we introduce a simple, S-shaped model that transparently explains the impacts of a wide range of maintenance strategies on the storm surge barrier performance. This model can be used for the communication with decision makers and to qualitatively assess on what aspects the underlying reliability model could be refined to optimally support the asset management. The added value of the model is illustrated on the basis of the asset management practice of the storm surge barriers in the Netherlands.

Keywords: Storm surge barrier, reliability modeling, asset management, maintenance, S-curve, bathtub curve, flood risk.

1. Introduction

Storm Surge Barriers are crucial structures for the flood protection of the Netherlands and many other Deltas around the world. Under normal conditions they are open to create an open connection between the sea and the estuary behind. Yet, in the rare event of a severe storm tide, they are closed to prevent dangerous water levels to protect the area around the estuary (Mooyaart and Jonkman, 2017).

In the Netherlands, strict performance requirements are applied to the storm surge barriers in order to minimize the probability that critical water levels of the inner basin are exceeded. That means that the storm surge barriers should be high enough to minimize the probability of substantial overload, strong enough to minimize the probability of structural failure, and reliable enough to minimize the probability of a failed closure (Mooyaart et al., 2025).

Rijkswaterstaat[a] applies ProBO (Probabilistic Operations and Maintenance) to keep the storm surge barriers always in perfect condition to sustain a high structural and operational reliability (Kharoubi et al., 2024). ProBO is a strict form of risk based asset management centered around highly detailed RA (Reliability and Availability) analyses that link the operational reliability to the Operations and Maintenance (O&M). Within ProBO, the RA models help to continuously monitor if the performance requirements are met and to optimize the operations and maintenance of the storm surge barriers.

Nevertheless, the asset management of the storm surge barriers encounters several issues with the applied RA models (Bakker et al., 2022; Rijkswaterstaat, 2022). The RA models are often perceived to provide conservative (=pessimistic) estimates, encouraging unnecessary investments (Mooyaart et al., in review). Besides, assessments with the RA models prove to be very laborious and therefore often fail to provide timely insight for urgent asset management decisions. Moreover, the models are hard to comprehend, causing that results are often hard to interpret (e.g. Rijkswaterstaat, 2022). Finally, there are concerns that not all relevant risks are adequately represented and that the underlying data are of poor quality, preventing adequate mitigation of the major performance killers (e.g. Bakker et al., 2025).

We argue that these issues may be related to the sometimes poorly understood, underlying assumptions and model choices. Among users, decision makers and even modelers. One assumption, particularly jumps out; the assumption of constant failure rate, implying no infant mortality, no aging during the useful life of components, timely preventive replacements and adequate routine maintenance (Bakker et al., 2022). Those aspects are however in practice not always met because it often proves hard to perform all required maintenance tasks (Pardo-Bosch and Aguado, 2015). This challenges the validity and usefulness of the applied RA models.

In this study, we introduce a simple, conceptual model that is intended to better understand the relation between and the consequences of model choices, underlying assumptions, and the level of detail. In section 2, we first introduce the conceptual model. Then, in section 3, we explain how the maintenance efforts, replacement strategies and model refinements affect the (perceived) performance. Finally, the conceptual model and its implications are discussed in section 4.

2. Conceptual model

2.1. *Relation O&M - performance*

Structures are always subject to degradation due to mechanical loadings from using the structure and environmental stresses (Van Noortwijk and Frangopol, 2004; Frangopol and Liu, 2007). As a result of the degradation, the structure's performance will decrease in time. This decrease can be compensated or reduced by means of maintenance, and when the performance does not comply with the requirements anymore, (parts of) the structure can be replaced or overhauled.

Over a certain period of time T the cumulative maintenance costs C_T are determined by the different maintenance activities performed. The average performance R_T during this period T depends on the efficiency E_T of the performed maintenance (and the way the structure is operated). When the performance R_T is inefficient the performance will be relatively low, regardless of the maintenance efforts.

In this study, we consider maintenance efforts efficient for a certain period T if they are close to Pareto optimal (Woodward et al., 2014). That means that it is not possible to achieve higher performance R_T for the same amount of maintenance costs C_T. What maintenance strategy is efficient strongly depends on the structure, its characteristic failure modes and the period T over which it is assessed.

[a]Rijkswaterstaat is the executive agency of the Ministry of Infrastructure and Water Management, dedicated to promote safety, mobility and the quality of life in the Netherlands

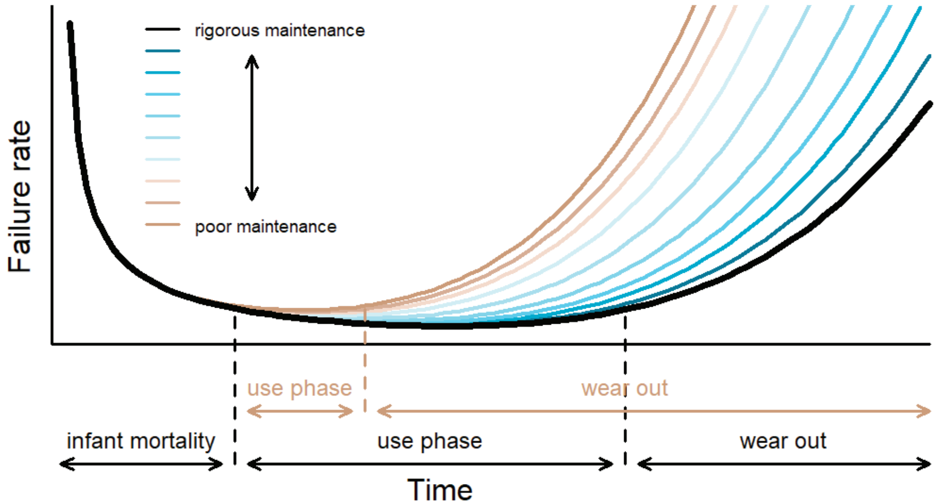

Fig. 1.: Bathtub curve (i.e. conceptual model of failure rate through time) for different Pareto efficient (undefined) maintenance strategies ranging from low (brown) to high (black) investment costs.

2.2. *Bathtub curve*

The bathtub curve is widely used to describe the development of failure and hazard rates through time (Moubray, 2001; Klutke et al., 2003). In maintenance engineering its usefulness and validity are however often challenged (Klutke et al., 2003). Nevertheless, a bathtub curve seems a useful concept to describe the development of the performance of storm surge barriers through time.

The bathtub curve distinguishes three phases (Figure 1). The phase of infant mortality is characterized by a decreasing failure rate, which reflects the influence of design and construction errors that become gradually resolved. In the use phase, the influence of design and construction errors has become negligible and the failure rate can be considered more or less constant. Of course, there are some variations as a consequence of slow degradation, inspections, testing and repair. Those variations are however relatively small during the use phase. During the wear out phase, the failure rate increases exponentially due to progressive degradation of parts of the structure.

The exact shape of the bathtub curve may diverge strongly from structure to structure and critically depends on the applied maintenance strategy and the configuration of its individual components. Sufficient and efficient maintenance efforts will promote a long use phase with relatively low failure rates (Figure 1, black line), whereas poor maintenance efforts will result in a shortened use phase with higher failure rates (brown line).

2.3. *The S-curve*

In this study, we hypothesize that the increase of performance of storm surge barriers (and other structures) with increasing (Pareto efficient) maintenance investments typically follows an S-shaped curve (Figure 2). If a storm surge barrier is poorly maintained, the barrier's performance is low (dark brown). Increasing the state of main-tenance of only a subset of the vital components or subsystems, will hardly increase the barrier's

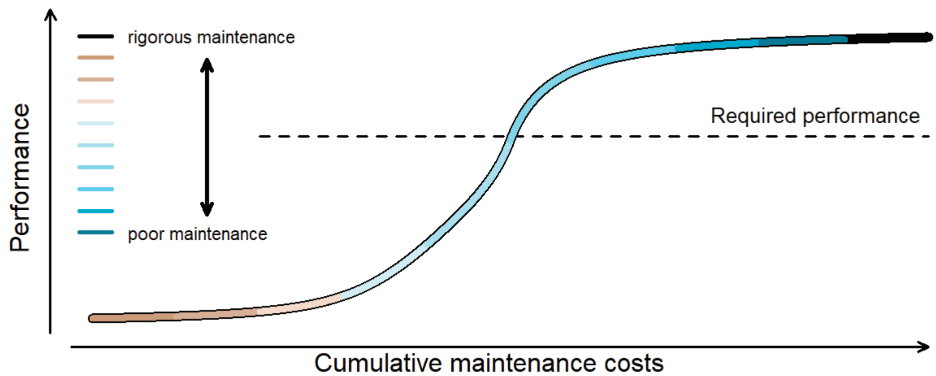

Fig. 2.: Conceptual model of the relation between investments in (Pareto) efficient maintenance efforts and the average structure's performance over planned service life. Note, that units are not necessary for this conceptual model.

performance (light brown). The failure probability of a closing operation will be dominated by those components and subsystems that are still in poor condition. Therefore, initially, the performance only grows slowly with increasing investment. At a certain level of efficient maintenance efforts, all vital components and subsystems will be at a fair 'base' state of maintenance. Roughly, that means that vital parts are replaced well before their malfunctioning can cause the failure of other parts and that their routine maintenance is at least such that the rate of degradation is not substantially higher than with 'perfect' maintenance. From this 'base' state on, every additional investment in efficient maintenance actions will cause a strong increase in performance (light blue). The state of maintenance approaches 'perfection' when there are hardly any trivial options for further refinement. For instance, if more frequent testing or shorter repair times hardly affect the performance and the replacement strategy is already close to optimal, i.e. neither too early, nor too late (Klanker et al., 2017)). From there on, further maintenance efforts will have minor effect. The increase of performance will slow down again and asymptotically approach its theoretical maximum performance (dark blue).

For the early stage use phase, moderate or large maintenance efforts won't make much of a difference for the failure rate (see Figure 1). Both strategies will lead to relatively high performance, i.e. low average failure rate (Figure 3). Yet, large maintenance efforts come with greater costs without a large additional benefit for the early stage performance. Although Pareto efficient, large maintenance efforts are not effective for the early use phase (rightmost part of the S-curve).

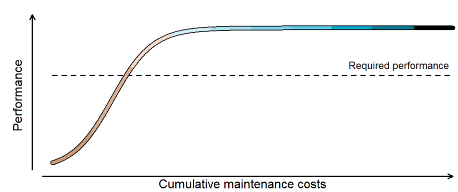

Fig. 3.: As figure 2, relation between (Pareto efficient) maintenance investments and average performance for *early* service life.

When the performance is well below the S-curve, the maintenance efforts are not efficient.

This may indicate unnecessary maintenance or an inefficient way of working. Performance above the S-curve is theoretically not possible. Innovative maintenance strategies, like drone inspections or predictive maintenance, may increase the potential performance, but will also shift the S-curve upwards. So, the S-curve depends on the assessed maintenance measures.

3. Operations & maintenance in practice

As mentioned before, the RA models that are applied in support of the O&M of the storm surge barriers rely on several important, but sometimes problematic assumptions and model choices. First, the assumption of constant failure rate is in practice rarely met, challenging the validity of the RA models. Second, the high level of detail makes the RA models incomprehensible, prone to errors and hard to apply. In practice, this leads to a high number of avoidable incidents, that are hard to effectively address. Third, the tendency to allow for a high amount of conservatism, often leads to unnecessary maintenance investments. In this section, the consequences of these assumptions and model choices are illustrated.

3.1. *The validity of constant failure rates*

The assumption of constant failure rates implies a negligible influence of infant mortality, timely replacements of parts before deterioration starts to affect the performance, and adequate routine maintenance. Here, routine maintenance refers to all activities that are performed on a regular basis to minimize the probability of failures of the storm surge barrier. It encompasses tasks like, daily operations management, general care or parts (e.g. lubrication), periodic inspection and testing to detect (future) failures, and minor repairs.

Sufficient daily operations management and care is a minimum precondition to maintain a high performance. Without, a high performance is not possible and the use phase will be extremely short. Since adequate daily operations management is a precondition of the RA models, the main levers in the RA models to optimize the maintenance are the test frequency and repair times. The possibility to adjust test intervals and repair times is however limited. For instance, sufficient general care of the mechanical parts requires periodic running of the machine to prevent it from getting stuck. This automatically sets a maximum to the allowed test intervals. In this way, the validity of the RA models is limited to more or less the blue-shaded area of the bathtub curves and the S-curve in Figure 4.

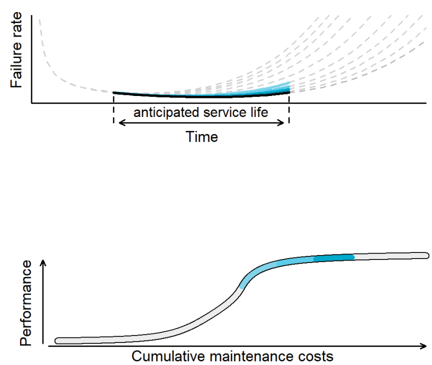

Fig. 4.: Valid range of RA models as applied by Rijkswaterstaat indicated by blue shading in bathtub curve (upper panel) and S-curve (lower panel)

Yet, in practice the storm surge barriers are maintained well outside the valid range of the RA models. First of all, it is questionable if the storm surge barriers are past the phase of infant mortality. All storm surge barriers are unique structures and their parts are often tailor made or used in a unique way(Walraven et al., 2022). This makes them susceptible to design errors and most storm surge barriers in the Netherlands have been encountering several design issues since their delivery (Walraven et al., 2022). Due to their infrequent use it may take considerable time before the design errors pop up and can be resolved. Moreover, some issues are only revealed during the preparation of the first major overhauls, that were not sufficiently taken into account in the design (Walraven et al., 2022; Trace-Kleeberg et al., 2023). Therefore, the infant mortality of

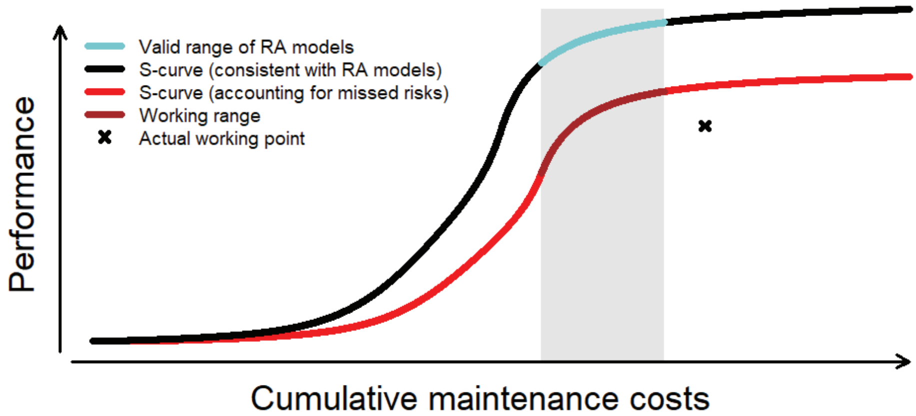

Fig. 5.: Difference between S-curve with (red) and without (black infant mortality and missed risks.

storm surge barriers may last much longer than typically anticipated, sometimes even until in the wear out phase.

Second, the high level of detail detail makes the RA models often fairly incomprehensible and prone to errors. As consequence, the storm surge barriers are often surprised by failure modes that were not included in the RA models. Effectively addressing the failures is often hard because of the incomprehensibility that makes the models hard to apply. This puts a lot of pressure on the O&M organization, often at the cost of the rigor of the maintenance activities. This lack of rigor increases the probability of maintenance induced failures which again puts even more pressure on the organization and so on.

The extended infant mortality of storm surge barriers and the relatively high probability of missed failure modes in the current generation of RA models substantially increases the failure rate (i.e. reducing the performance) during the anticipated service life of storm surge barriers (compare black and red lines in Figure 5). Because, the missed failure modes were not anticipated, it is unlikely that there are enough resources to adequately mitigate them all, shifting the S-curve even further down. Yet, since the the RA models are hard to work with and the O&M organization is already under pressure, it is unlikely that the maintenance investments are Pareto efficient (black cross).

3.2. *Conservatism and efficiency*

Obviously, the relation between O&M and performance, and consequently the exact shape of the S-curve are uncertain. These uncertainties have different sources. First of all, there is uncertainty around the applied data. As mentioned earlier, storm surge barriers are unique structures, prototypes (Walraven et al., 2022). Moreover, storm surge barriers are rarely operated in full storm conditions. The estimated frequency of storm closures typically ranges from a couple of times per year (e.g. the Hollandsche IJssel Barrier) to once per 10 year (e.g. the Maeslant Storm Surge Barrier). As a consequence, the performance of the storm surge barriers, and the applied failure data cannot always be based on field observations. Therefore, failure data are usually retrieved from failure data bases or elicited from experts, both involving a lot of uncertainty.

Second, uncertainties may result from missing failure mechanisms (see subsection 3.1) , risk mitigating activities and the dependencies between them (incompleteness). In a recent safety assessment, it was for instance concluded that the Maeslant Storm Surge Barrier does not comply with the official safety standards, partly due to too little insight into a large number of potentially important failure mechanisms that are not accounted for in the current risk analysis (Rijkswaterstaat, 2022).

Third, the exact relation how maintenance impacts the the performance through time is unknown. In practice, preventive maintenance strategies provide very little insight into the degradation because structures or their subsystems are ideally replaced before failure. And even in case of corrective maintenance, the learning potential is small because parts are typically replaced when the modeled failure probability becomes too high, well before it actually fails. Also, insufficiently maintained structures are unlikely to offer a solution, since insufficiently maintained structures often also lack a good monitoring and registration of failures.

In practice, the uncertainty is often dealt with by using conservative (=pessimistic) estimates (Figure 6, red line). For example, RA models of the Dutch storm surge barriers often base the component failure rates on the 95% quantile provided by failure databases and apply maximum allowed repair times as MTTR. One potential advantage of the conservatism is that new insights do not automatically result in not complying with the performance requirements (Bakker et al., 2022). Yet, conservatism may also lead to superfluous (i.e. inefficient) maintenance efforts and sometimes even to unnecessary system upgrades.

4. Optimizing maintenance costs

As mentioned earlier, storm surge barriers have three principal failure modes; structural failure, operational failure (e.g. failure to close) and hydraulic overload (Mooyaart et al., 2025). Usually, the performance of storm surge barriers is dominated by their operational reliability (Mooyaart et al., 2025). The life cycle costs, on the

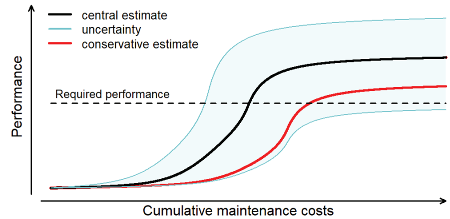

Fig. 6.: S-curve including uncertainty. Black line represents the central estimate of the Pareto optimal maintenance investements, the blue shading its uncertainty, and the red line a conservative estimate.

other hand, are usually dominated by the life cycle maintenance of structural parts like the steel gates, concrete foundation and bed protection (Klatter et al., 2019) and internal costs of Rijkswaterstaat (De Ruig et al., 2021). Those are, however, not explicitly modelled in the RA models. This implies that the current generation of RA models cannot effectively support the optimization of the life cycle maintenance strategy.

If cost reduction is the goal, one should look for other maintenance strategies of the structural parts without compromising the structural reliability (too much). Optimization models for the maintenance of infrastructure have been readily available for many years (e.g. Frangopol and Liu, 2007; Van Noortwijk and Frangopol, 2004; van den Boomen et al., 2020). Yet, they haven't been applied to optimize the life cycle management of storm surge barriers so far.

If increasing the performance is the goal, one should focus on improving the operational reliability. It is however unlikely that this can be achieved by more advanced or more rigorous maintenance efforts. The current maintenance strategy seems in theory sufficient, but it is poorly supported to the current generation RA models. Too often, the O&M organization is confronted by unanticipated failure modes, causing a chain reaction of inefficient and delayed maintenance. To anticipate this, RA models should better represent the main failure modes and become more comprehensible.

What aspects should be explicitly included in the model will differ from case to case. This can be explored by using the proposed S-shaped conceptual model that relates Pareto efficient maintenance investments to performance.

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